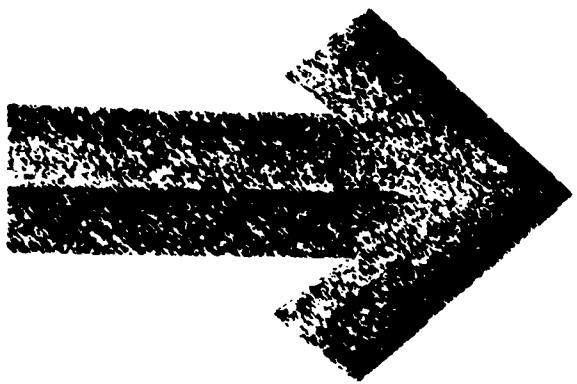

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John Jay Hopkins Laboratory
for Pure and Applied Science

A USE FOR RADIOISOTOPES IN ABLATION EXPERIMENTS

The Nuclear/Chemical Pulse Reaction Propulsion Project

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A USE FOR RADIOISOTOPES IN ABLATION EXPERIMENTS

An extension of the experimental ablation study, currently being conducted by the experimental group of the Orion Project, can be accomplished by the addition of radioactive tracers into the material of the ablation sample. The existing expanded plasma and shock apparatus would require only minor modification; moreover, the current program could be continued and conducted simultaneously with the proposed tracer program.

INTRODUCTION

There are two general methods utilizing tracers which can be used to study ablation in the expanded CH_2 plasma and shock experiment. The first, and simplest, is to add a radioisotope, preferably a gamma emitter, homogeneously to the sample material. A beta emitter could be used under certain conditions where very thin films are investigated. The sample activity would then be mapped with a suitable small angle detector. After exposure to the plasma, the sample would be re-mapped with the detector. Changes in the count rate would indicate ablation and material transport on the surface.

The second method would be to deposit several different radioisotopes in concentric rings across the sample surface, as shown in Figure 2. By the use of a pulse height channel analyzer as a detector to discriminate energy, the sample would be mapped before and after ablation for the respective tracer activity. In this method, total ablation could again be measured; but more significantly, material transport on a quantitative basis could be determined. Thus, mapping the sample for a particular radioisotope would measure the results of melting ablation in terms of the original tracer and, therefore, mass distribution. Specific details of both methods will be discussed, as well as counting correction factors, methods of measurement, counter designs, and a survey of possible radioisotopes.

METHOD 1 - HOMOGENEOUS TRACER

In this method, as outlined above, the radioisotope is deposited homogeneously in the sample material. It is undesirable for several reasons for the tracer to be deposited throughout the entire thickness of the sample.

The current experiments use aluminum samples 5 inches in diameter and about 2 inches thick. Some thickness << 2 inches would be adequate for the tracer deposit. This is based on an estimate of the total ablation and upon self-shielding and back-scattering of the emitted radiations. Discussing in this section only the first of these factors, an estimate of maximum ablation can be made from an analysis of the current experiments. Consider the maximum depth of material removed is X_1, see Figure 1, we also define:

X_o = original surface.

X_b = boundary between traced and pure sample material.

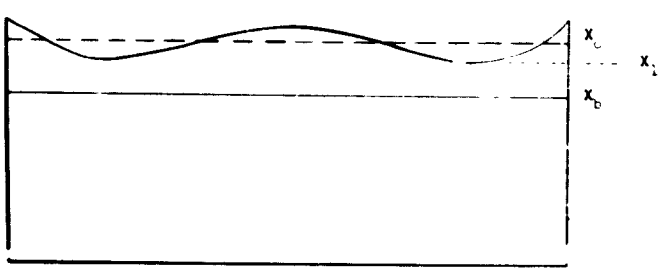


FIGURE 1

It is necessary that X_b be greater than X_1 for a complete determination of the ablation.

A scintillation counter design will be presented later, but for now assume a simple radioactive decay with a counter of sufficiently small solid angle and area for scanning the sample surface. It should be understood that some of the disintegrations emit particles which do not reach the detector. So long as the counting geometry remains fixed and the detector sensitivity is independent of time, the counting rate or activity is proportional to the disintegration rate. That is

$$(1) \qquad A = K\frac{dN}{dt}$$

where K is a proportionality constant and A is the activity in counts per cm^2 per unit time. With this definition the following discussion will be in terms of activity.

Let S_o be the specific activity of the sample in disintegrations/cm^3-sec, X is a very thin thickness of traced material so that self-shielding can be neglected, and λ the decay constant, then

$$(2) \qquad A_o = \int_o^X S_o dx = S_o X \qquad \left[\text{dis/cm}^2\text{-sec}\right] .$$

From the assumption of simple decay for a single isotope.

$$(3) \qquad \frac{dN}{dt} = \lambda N \qquad \text{or} \qquad A = \lambda N \qquad \text{and} \qquad A = A_o e^{-\lambda t} .$$

Combining with (2) at $t > o$

$$(4) \qquad A = S_o X e^{-\lambda t} .$$

At time $t = o$ before ablation $X = X_o$ so

$$(5) \qquad X_o = \frac{A_o}{S_o} .$$

After ablation at $t = t_1$, the time of measurement,

$$(6) \qquad X = \frac{A}{S_o e^{-\lambda t_1}} .$$

The difference in material thickness is

$$(7) \qquad X_o - X = \frac{A_o}{S_o} - \frac{A}{S_o e^{-\lambda t_1}} .$$

Thus, by knowing S_o from preparation of the sample and by measuring the activity before and after exposure to the plasma, the ablation thickness can be calculated.

This method offers the advantage of measuring relatively small amounts of ablation, limited primarily by detector sensitivity and counting statistics.

A highly shielded detector subtending the entire 5-inch sample and having low background count for measuring the total activity could be designed to measure evaporative ablation of metals as well as non-conducting thin films. Counter designs and an analysis of the factors affecting the measurement will be discussed later.

METHOD 2 - TRACERS IN CONCENTRIC RINGS

This method is an extension of the previous technique and offers the additional advantage of measuring mass transport resulting from melting ablation. Several species of radioisotopes are deposited in concentric cylindrical rings in the sample material. As before, the radioisotopes are deposited to a thickness X which is greater than the depth of maximum ablation.

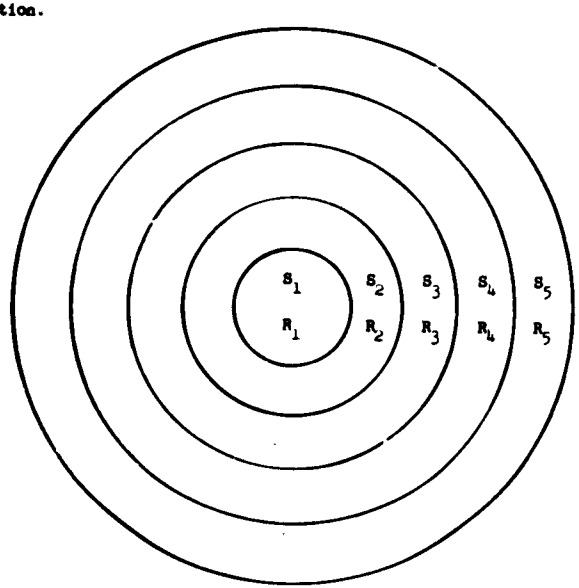


FIGURE 2

Ablation Sample with Tracers Deposited in Concentric Rings

Consider the sample, as shown in Figure 2, of five radioisotope species, each with a characteristic emission spectrum, preferably as simple as possible. A particular beta or gamma energy would be selected from each radioisotope; then, with the use of an energy discriminator associated with the detector, the sample would be mapped and the count rate or "activity" $\frac{dA}{dt}(E_i)$ plotted as a function of position. The same measurement would be repeated after ablation and corrected for radioactive decay.

Denote S_i as a radioisotope species and R_i as the corresponding cylindrical region bounding S_i (see Figure 2). Thus,

(8) $$\frac{dA}{dt}(S_i)^b = \frac{dA}{dt}(R_i)^b \qquad i = 1 \text{ to } 5$$

where $\frac{dA}{dt}(S_i)^b$ is the discriminated count rate of isotope of energy, E_i.

and $\frac{dA}{dt}(R_i)^b$ is the count rate in the region R_i.

The superscript "b" indicates a measurement before ablation.

If the counting is accomplished over a time Δt, Eq. (1) becomes

(9) $$\frac{dA}{dt}(S_i)^b \Delta t = A(S_i)^b \qquad i = 1 \text{ to } 5$$

or

(10) $$A(S_i)^b = A(R_i)^b \qquad i = 1 \text{ to } 5$$

This equation is the first balance equation and states that the activity in region R_i is due only to the corresponding radioisotope S_i. This is somewhat trivial, but if mixing at an interface between two species occurred during preparation of the sample, the true boundary could be determined.

Consider now the general case after ablation. A radioisotope, say S_1, will have some distribution throughout all regions of the sample, and similarly for the other species present. This will result from the action of pressure gradients during the process of melting ablation. A certain fraction of material containing S_1 may also be lost to the system by evaporative ablation denoted by $E_L(S_1)$. The new balance equation is

$$(11) \qquad \frac{dA(S_i)^a}{dt} = \sum_{j=1}^{5} \frac{dA(R_j)^a}{dt} + E_L(S_i) \qquad i = 1 \text{ to } 5$$

where the superscript "a" indicates a measurement after ablation. From consideration of radioactive decay we know

$$(12) \qquad \frac{dA(S_i)^a}{dt} = \frac{dA(S_i)^b}{dt} e^{-\lambda_i t} \qquad i = 1 \text{ to } 5$$

Substitution into (11) gives

$$(13) \qquad \frac{dA(S_i)^b}{dt} e^{-\lambda_i t} = \sum_{j=1}^{5} \frac{dA(R_j)^a}{dt} + E_L(S_i) \qquad i = 1 \text{ to } 5$$

After dividing through by the LHS, we have an expression for the fraction of original radioisotope now found in each region R_i and the fraction evaporated:

$$(14) \qquad 1 = \frac{\sum_{j=1}^{5} \frac{dA(R_j)^a}{dt}}{\frac{dA}{dt}(R_i)^b e^{-\lambda_i t}} + \frac{E_L(S_i)}{\frac{dA}{dt}(R_i)^b e^{-\lambda_i t}} \qquad i = 1 \text{ to } 5$$

Since all quantities are actually measured except $E_L(S_i)$, we can now calculate the evaporative ablation of each specie and, therefore, each region. This activity is related to a certain thickness of material by an equation similar to Eq. (6) of Method 1. One limitation is that radioisotopes of the sample element will, in general, not be used for all the S_i because of half life, decay scheme, disintegration energy, or availability. They must, however, have similar latent heats of fusion and vaporization as the sample material.

A measurement of the total activity with an energy discriminating counter would permit a direct calculation of total ablation. Thus, $E_L(S_i)$ from Eq. (14) can be checked independently. Method 2 then offers considerably more information with nearly identical limitations, so would usually be preferred.

FACTORS AFFECTING THE MEASUREMENT

An accurate measurement of the tracer activity places certain requirements upon the counting equipment as well as upon experimental technique. Since this is a relative measurement, it is essential that sample counting be conducted under conditions as similar as possible. If this is accomplished, most correction factors can be omitted in the ablation calculation. The one exception, as will be shown, is self-shielding of a beta emitter.

The disintegration rate N_t for a simple decay is related to the counting rate A_c by

$$(15) \qquad A_c = N_t \frac{\Omega}{4\pi} \eta \tau A_f B_f C_f$$

where

Ω is the solid angle subtended by the counter.

η is the counter efficiency.

τ is the counter dead time.

A_f is the absorption factor for air and the counter window.

B_f is the backscattering factor.

C_f is the self-shielding factor.

These factors will now be discussed in detail.

1. Counter Efficiency and Geometry

If the same counter is used under conditions of identical geometry, the factors Ω, η, τ, and A_f are then constants of the experiment and need not be entered in the calculations. However, calibration of the counter with a standard source is a very strict requirement and is absolutely essential to insure constancy of these factors, particularly so when measurements are conducted over a period of days or weeks.

2. Scattering

The scattering of radiation into the detector influences the measurements by increasing the count rate for a given tracer deposit. This background of scattered radiation arises from large angle or multiple scattering

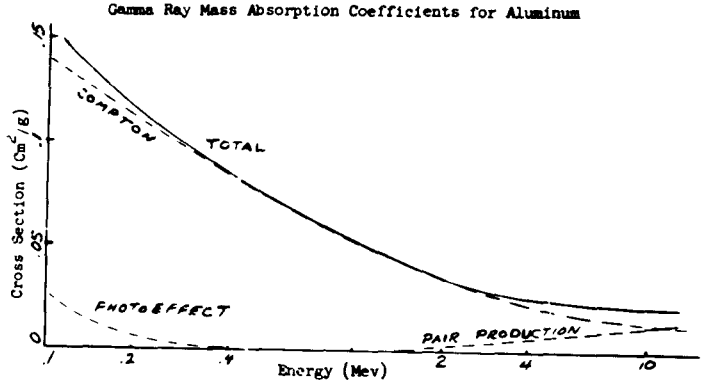
from the surroundings and backscattering from the source mounting. The former can be held constant by keeping the counting geometry fixed and relatively low by collimating and shielding the detector. Placing the counter and sample in an evacuated chamber would further reduce air scattering and relax the collimation requirement. This has a particular advantage when counting total sample activity in a single measurement.

In both Methods 1 and 2, the radioisotopes are deposited on a thick backing of aluminum. This is defined as a thickness which is several mean free paths of the emitted radiation. In the case of a beta emitter deposited upon a thick backing, some betas emitted in a direction away from the detector will be scattered back by multiple Rutherford scattering. This factor increases up to some saturation value, becoming constant for a thickness of about .2R, where R is the range of the beta particle. For 2 Mev betas the range in aluminum of density 2.7 g/cm^3 is approximately 1 g/cm^2. The ablation sample is of the order 2 inches thick = 5.08 cm, giving d = ρx = (5.08)(2.7) = 13.72 g/cm^2, which is much greater than .2R = .2 g/cm^2. The backscattering factor B_f for aluminum is approximately 1.3, and for iron approximately 1.6. Moreover, the saturation factor is independent of beta energy between .3 Mev and 2.3 Mev. Thus, where ablation of very thin films is being investigated by use of several tracers, as in Method 2, beta emitters having emission energy within this range could be used with a constant backscattering factor. The correction then in a relative measurement could be omitted in the ablation calculations.

Gamma radiation on the other hand is scattered back into the detector by Compton scattering. Discussion will be limited to gamma energy greater than electron binding energies so that coherent scattering can be neglected. Photonuclear reactions will also be neglected because peak gamma energy will be less than nuclear threshold. Two other processes then compete with Compton scattering in the energy range .1 Mev to 5 Mev, they are pair production and photoelectric effect. Compton scattering, however, is the predominant process in the region of intermediate energy for all Z, whereas photoeffect is important only for low energy and high Z, and pair production for high energy and high Z. Aluminum cross sections are plotted in Figure 3.

FIGURE 3

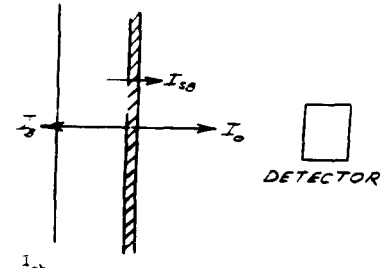
Gamma Ray Mass Absorption Coefficients for Aluminum



The backscattering factor for gammas will be defined in terms of the forward intensity I_o and the backscattered intensity I_{sb},

$$B_f = \frac{I_o + I_{sb}}{I_o} = 1 + \frac{I_{sb}}{I_o} \quad . \tag{16}$$

By illustration this is



where $I_b = I_o$, and $\frac{I_{sb}}{I_o}$ is the fraction of the incident beam backscattered into the detector.

In measuring the activity of a homogeneously deposited gamma emitter, as in Method 1, the backscattering factor before and after ablation of the sample is constant. This is evident by considering the Klein-Nishina calculation of the scattering of an incident gamma beam at an angle θ. The solution, based on quantum mechanics using the Dirac equation for the electron, is

$$(17) \qquad I_s = \frac{I_o}{r^2} \frac{h\nu'}{h\nu} K(\theta)$$

where I_o is the intensity of the incident beam of γ-rays.

I_s is the intensity of the scattered beam at angle θ.

r is the distance from the scattering electron.

$h\nu$ is the incident gamma energy.

$h\nu'$ is the scattered gamma energy.

and $K(\theta)$ is the differential cross section for the number of gammas scattered per electron per unit solid angle Ω in direction θ.

This is given by

$$(18) \qquad \frac{d\sigma(\theta)}{d\Omega} = K(\theta) = \frac{r_o^2}{2} \left\{ \frac{1}{\left[1+\alpha(1-\cos\theta)\right]^2} \cdot \left[1 + \cos^2\theta + \frac{\alpha^2(1-\cos\theta)^2}{\left[1+\alpha(1-\cos\theta)\right]} \right] \right\}$$

where $r_o = \frac{e^2}{m_e c^2} = 2.818(10)^{-13}$, the classical electron radius.

$$\alpha = \frac{h\nu}{m_e c^2}$$

Note that $K(\theta)$ is a function of incident gamma energy and angle θ of the scattered gamma. The scattered intensity I_s is then a function of incident energy and angle as seen by using

$$(19) \qquad h\nu' = \frac{h\nu}{1+\alpha(1-\cos\theta)} .$$

Substitution of Eq. (19) into (17) gives

$$(20) \qquad I_s = \frac{I_o}{r^2} \frac{K(\theta)}{1+\alpha(1-\cos\theta)} .$$

This is equal to I_{sb} of Eq. (16) if θ is within the angle subtended by the detector, so

$$(21) \qquad \frac{I_{sb}}{I_o} = \frac{K(\theta)}{r^2\left[1+\alpha(1-\cos\theta)\right]}$$

and

$$(22) \qquad B_f = 1 + \frac{K(\theta)}{r^2\left[1+\alpha(1-\cos\theta)\right]} .$$

This shows that for a given isotope emitting gammas of energy $h\nu$, the backscattering factor, as stated above, is constant for fixed counting geometry.

The fact that $K(\theta)$ is relatively small[3] for backscattering near $\theta = 180^\circ$ helps considerably to reduce the correction even in an absolute measurement. For $\alpha = 1$, approximately .03 of the scattered gammas are backscattered into a cone subtending 20° from the axis; i.e., $\theta = 160^\circ$ to 180°. The total Compton cross section for aluminum at $\alpha = 1$ is $\mu_c = \mu_s \approx .084$ cm^2/g, Compton scattering being the only significant process of attenuation at this energy. As before, the ablation sample thickness is $d \approx 13.6$ g/cm^2, thus

$$(23) \qquad I = I_o e^{-\mu d} = I_o e^{-1.142} = .319\, I_o$$

The fraction scattered then is $\approx .68$ of the incident intensity. Of this, 3% is backscattered into the 20° cone, which is now 2% of I_o. For some measurements this is equivalent to statistical counting errors.

Method 2 for gammas presents a somewhat different problem with several radioisotopes deposited in the sample, each emitting gammas of different energy. It is apparent that $K(\Theta)$, being a function of energy, will not be constant for a given backscattering angle. The fact, however, that the total Compton cross section for $\alpha > 1$ decreases rather slowly with increasing energy, does permit relative measurements to be made quite accurately with the use of an energy discriminator.

Of the several radioisotopes present in the sample, the largest contribution to primary scattering will come from the species emitting the lowest energy. As calculated previously for $\alpha = 1$, the fraction of incident gammas scattered is $\approx .68$; for $\alpha = 4$ (≈ 2 Mev gammas), the fraction is $\approx .45$. The fraction then backscattered into a 20° cone is approximately .02 and .01, respectively. To correct for this difference, consider a spread in gamma energy of the radioisotopes between .5 Mev and 2 Mev ($\alpha \approx 1$ to 4). The maximum energy backscattered into the 20° cone is for $E = 2$ Mev, $\alpha \approx 4$, and $\Theta = 160^\circ$, thus

$$E' = \frac{E}{1+\alpha(1-\cos\Theta)} \approx .229 \text{ Mev} \qquad (24)$$

By discriminating gammas below this energy or perhaps below an energy just slightly less than .5 Mev, the backscattering difference will be reduced to such a point that in a relative measurement no correction need be applied. Another difficulty does, however, exist since two scattered gammas of approximately .229 Mev each, might be simultaneously absorbed in the detector, producing a pulse of $\approx .5$ Mev. Coincidence of several multiple scattered gammas might also have the same result. Shielding of the detector then becomes an even more important requirement than before. The use of anticoincident counting also suggests itself and will be discussed later as a counter design.

So far as scattering is concerned, by meeting certain requirements in the choice of radioisotopes, in counting geometry, and in the counter's electronic circuit, the corrections may be neglected for both Method 1 and 2. This is true for counting either beta or gamma emission.

3. Self-Shielding

The absorption or attenuation of radiation in the source itself is largely determined by the energy of emission and source thickness. The self-shielding factor C_f can be calculated approximately if absorption is assumed to be exponential with an absorption coefficient independent of depth of emission. Let A_o be the activity of a plane source which has the same strength as the thick sample. Also, design the experiment such that the sample to detector distance L_o is very much greater than the source thickness X. The activity then of a thickness dx is

$$dA = A_o e^{-\mu x} \frac{dx}{X} \quad . \qquad (25)$$

The measured activity is

$$A = \int_o^X \frac{A_o}{X} e^{-\mu x} dx = \frac{A_o}{\mu X}(1 - e^{-\mu X}) \qquad (26)$$

which gives the self-shielding factor

$$C_f = \frac{A}{A_o} = \frac{(1 - e^{-\mu X})}{\mu X} \quad . \qquad (27)$$

Consider for a moment Eq. (2), where self-shielding was neglected by assuming the radioisotope deposit was very thin. With $A_o = S_o X$, Eq. (26) becomes

$$A = \frac{S_o}{\mu}(1 - e^{-\mu X}) \quad . \qquad (28)$$

For $\mu X < 1$, the exponential term can be expanded in a series, giving

$$A = \frac{S_o}{\mu}\left[1 - \left(1 - \mu X + \frac{(\mu X)^2}{2} - \ldots\right)\right] \quad . \qquad (29)$$

By neglecting terms higher than second order

$$(30) \qquad A \approx \frac{S_o}{\mu}\left(\mu X - \frac{(\mu x)^2}{2}\right) = S_o\left(X - \frac{\mu X^2}{2}\right) .$$

With μX small enough, either by no absorption ($\mu \to 0$) or by X being very thin, Eq. (30) can be reduced further to Eq. (2). Since μ is relatively small for gammas and decreases with energy, this approximation is valid to within 1% for gammas of energy >.5 Mev.

In single exposure experiments, non-uniform ablation has been observed from 10 to 20 mils. For purposes of estimation consider a radioisotope deposited to a thickness of .1 cm The linear absorption coefficient for .5 Mev gammas is $\approx .2\ cm^{-1}$. The calculation of the activity with and without the $\mu X^2/2$ term gives A = .099 and A_o = .1, respectively. This is a difference of only 1%, becoming even less for higher energies (smaller μ). The correction factor of Eq. (27) is C_f = .99. For betas of .5 Mev the effective μ is quite different, being $\approx 16.9\ cm^{-1}$. Using Eq. (30) as above, the difference is ≈ 8%. This, of course, violates the condition $\mu X << 1$, but by comparison shows that the exact Eqs. (27) or (28) must be used for beta self-shielding and that the correction factor is not negligible, except possibly for very thin films.

In summary, the ablation in both Methods 1 and 2 can be calculated by a relative measurement of the activity. This simplifies the experiment considerably and reduces the systematic errors that might otherwise develop if a series of corrections were necessary.

METHODS OF MEASUREMENT

Measuring the activity of the sample as a function of position requires that the counter be collimated to a very small solid angle. This is so that the scanning area can be kept reasonably small. On the other hand,

the specific activity must be high enough to afford adequate counting statistics. Consider 1 mc of Na^{22} (E_γ = 1.276 Mev) deposited homogeneously to a thickness of .1 cm. The specific activity is

$$(31) \qquad S_o = \frac{3.7(10)^7}{V}\left[\frac{dis}{cm^3\text{-}sec}\right]$$

$$S_o = \frac{3.7(10)^7}{.19635} = 1.8844(10)^8\left[\frac{dis}{cm^3\text{-}sec}\right] .$$

For the initial thickness of .1 cm, the activity is

$$(32) \qquad A = 1.8844(10)^7\left[\frac{dis}{cm^2\text{-}sec}\right] .$$

Let the detector be collimated and shielded to scan an area of .25 cm^2 subtending a solid half angle of 1°, thus

$$(33) \qquad \Omega = \int_0^1 \int_0^{2\pi} \sin\Theta\, d\Theta\, d\phi = 2\pi(.00015) .$$

The count rate measured with the counter is

$$A_c = \frac{\Omega}{4\pi} A \cdot \quad \text{(Area Scanned)}$$

$$(34) \qquad A_c = \frac{2\pi(.00015)}{4\pi} \times 1.8844(10)^7 \times .25$$

$$A_c = 353.33\ \text{cps} \quad \text{or} \quad <1200\ \text{cpm}.$$

The following tables illustrate the counting rates that can be measured for ablation of 1 mil and 10 mils. Table 1 shows the counting rates for a scanning area of .5 cm^2, and Table 2 for .25 cm^2. The specific activity is constant in both tables (A_s = 1.3844 dis/cm^3-sec), and values are calculated for three initial deposit thicknesses of X = .1, .05, and .025 cm.

TABLE 1

Relative Count Rates in Counts per Minute for Scanning Area of .5 cm^2. Specific Activity is Constant at 1.3844 dis/cm^3-sec.

Initial Thickness (cm)	ΔX = 0	ΔX = 1 mil	ΔX = 10 mils
X = .1	42,399	41,361	31,031
X = .05	21,200	20,660	10,430
X = .025	10,600	9,870	-

TABLE 2

Relative Count Rates in Counts per Minute for Scanning Area of .25 cm^2. Specific Activity is Constant at 1.3844 dis/cm^3-sec.

Initial Thickness (cm)	ΔX = 0	ΔX = 1 mil	ΔX = 10 mils
X = .1	21,200	20,660	15,515
X = .05	10,600	9,930	5,215
X = .025	5,300	4,969	-

An estimate of errors in the measurements can be made by considering two extreme cases from the above tables. For 1 mil ablation from Table 2, with initial thickness .1 cm, the change in measured activity is

$$\Delta A = 21{,}200 - 20{,}660 \pm \text{error} \quad [\text{cpm}]$$

$$\Delta A = 540 \pm \text{error} \quad [\text{cpm}] \qquad (35)$$

The most probable error (MPE) is

$$MPE = \pm \sqrt{MPE^2_{\Delta x=0} + MPE^2_{\Delta x=1}} \quad [\text{cpm}]$$

$$MPE = \pm \sqrt{(.6745\sqrt{6})^2_{\Delta x=0} + (.6745\sqrt{6})^2_{\Delta x=1}} = \sqrt{98^2 + 96^2} \qquad (36)$$

$$MPE = \pm 43 \text{ cpm}$$

so

$$\Delta A = 540 \pm 43 = 540 \pm 8\% \text{ cpm.}$$

Ablation of 10 mils for the same initial thickness gives

$$\Delta A = 21{,}200 - 15{,}815 \pm \text{error}$$

$$\Delta A = 5385 \pm \text{error} \qquad (37)$$

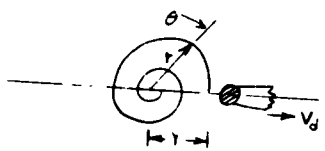
and

$$MPE = \pm 41 \text{ cpm}$$

$$\Delta A = 5385 \pm 41 = 5385 \pm .7\% \text{ cpm.} \qquad (38)$$

It is apparent then that there is more uncertainty in the experiment when the deposit thickness is very much greater than the ablation. As a general rule, optimizing the deposit thickness to twice the depth of ablation would give reasonable counting statistics and keep the error to within a few per cent.

One method of using the small solid angle counter would be to continuously move the detector and measure the count rate as a function of position. This could be accomplished with a machine lathe by placing the sample in the chuck and rotating it at some angular velocity $\dot{\theta}$. The detector would be placed on the compound cross feed, moving radially at a velocity V_d. The resulting scanning path then would be a spiral. Consider the following figure with analysis:



(39)
$$dr = a\, d\theta$$
$$r = a\int_0^{2\pi} d\theta = Y = V_d t$$

where Y is the distance traveled by the detector in time t. Also,

(40)
$$dr = V_d dt = a\, d\theta \qquad \text{and finally}$$
$$\frac{d\theta}{dt} = \frac{V_d}{a} = \dot{\theta} .$$

Thus, for a given measurement with known $\dot{\theta}$ and V_d, the spiral constant "a" can be calculated. The count rate would usually be plotted as a function of path length, which is defined as

(41)
$$dS = r\, d\theta \qquad \text{where} \qquad r = a\,\theta$$
$$S = \int_0^{\theta} a\,\theta\, d\theta = \frac{a\theta^2}{2} .$$

The counter could, of course, be used equally as well for static measurements, particularly where statistical errors are to be kept small. A map could be made of activity for several fixed positions, counting for as long as necessary to obtain the desired accuracy. By proper choice of $\dot{\theta}$ and V_d a slowly moving detector could produce results approaching that of a static measurement. The necessary velocities could be determined empirically.

Another method of measuring the activity is by a large detector or grouping of several detectors subtending the entire sample. By housing the counter and sample in an evacuated chamber to reduce air scattering, very low levels of activity could be measured.

COUNTER DESIGNS

A scintillation counter would be the most desirable for this experiment because of its high efficiency in counting intense beta and gamma activity. Depending upon the detector used, recovery times can be attained to the order of 10^{-8} sec. Usually Tl-activated NaI is preferred as a scintillator for gamma detection, while anthracene is used for betas.

A design for the small angle scanning counter is shown in Figure 4. It consists of a crystal mounted on a photomultiplier tube, such as an RCA 5819. Actual shield and crystal dimensions would depend upon the maximum particle energy emitted by the tracer. The entire assembly could be positioned statically for a measurement or clamped in the compound cross feed of a lathe as discussed previously.

Figure 5 is a design of a large angle counter for use in measuring total sample activity. Since the chamber is evacuated, the counter would be particularly useful for measuring the activity of a beta emitter deposited in a thin film. A large 5-in. diameter crystal could be used for maximum counting efficiency. Measurements could also be made by placing several absorbing cylindrical rings of different radii over the sample, the result being a masking of different areas from the counter. The absorbers must, however, absorb all incident primary radiations and all secondary radiations produced within them. As a refinement to both Methods 1 and 2, the rings could be used as a Compton shield for gammas and as a total absorber for betas.

A SHORT SURVEY OF RADIOISOTOPES

The following tables list several radioisotopes having emission energies and decay properties desirable for this experiment. Only the energies of use in this experiment are listed. Refer to References 6, 7, and 9 for the complete decay schemes.

TABLE 3

A FEW GAMMA SOURCES

Isotope	Half-Life	Usable Gamma Energy (Mev)
Sodium-22	2.6 y	1.276
Scandium-46	84 d	1.119, .885
Iron-59	45 d	1.289, 1.098
Cobalt-60	5.27 y	1.333, 1.173
Zinc-65	245 d	1.119
Strontium-85	64 d	.513
Niobium-95	35 d	.768
Mercury-203	47 d	.279
Bismuth-207	8.0 y	1.771, 1.064, .57
Cesium-137	2.66 y	.662

TABLE 4

A FEW BETA SOURCES

Isotope	Half-Life	Usable Beta Energy (Mev)
Calcium-45	164 d	.256
Rubidium-86	18.7 d	1.776, .698
Cerium-144	282 d	.309, .175
Thallium-204	4 y	.764
Strontium-90	28 y	2.25, .544
Phosphorus-32	14.2d	1.71
Thulium-170	129 d	.968, .884
Cesium-137	266 y	.514, 1.17

A BRIEF DISCUSSION OF SAMPLE PREPARATION

Two rather simple methods appear possible for making thick uniform tracer deposits; both, however, have certain limitations. Many of the radioisotopes listed in the survey tables are produced by neutron capture in a stable parent isotope. An alloy or mixture of the sample material with the parent isotope could first be machined to the desired dimensions and then exposed to the neutron flux of the TRIGA reactor. Attaching this to a non-radioactive backing would be the final step in preparing the ablation sample. The other method is to add a radioisotope directly to the sample material by mixing in the molten state. This would necessarily be done in a hot laboratory having metallurgical and shop facilities for melting and machining radioactive materials.

Facilities for either method exist at General Atomic; so a choice between the two would depend upon relative cost of materials as well as upon the cost of hot lab equipment compared to a standard machine shop. The one paramount requirement is that the tracer deposit be uniform. Many factors, of course, control this result, such as choice of radioisotopes, uniform neutron flux, sample thickness, phase diagrams of the metal systems, etc.; consequently, some experimentation would be desirable and perhaps necessary to establish a reliable method of preparation. In general, the first method of pile irradiation seems the most practical and is limited primarily by a choice of parent isotopes having fairly large neutron capture cross sections. Fortunately, with the TRIGA neutron flux, this is not a very serious limitation.

Several methods are known for preparing thin films of varying uniformity, such as thermal vacuum evaporation, electrodeposition, electromagnetic deposition, solvent evaporation, pile irradiation (as above), and adsorption. Those interested in details of these techniques should see Reference 8.

CONCLUSION

Based on the analysis in this report, ablation can be measured by tracer techniques to very high accuracy, in fact to almost any desired accuracy. This is accomplished for a given specific activity by adjusting the counting times to obtain the desired statistics, which largely determine

the accuracy in a relative measurement of this kind. Moreover, it may be that for very small ablation, as in the case of non-conducting thin films, the use of tracers will be the only reliable means of measurement. Many possibilities, of course, exist for improving the experiment, but the aim of this paper has been to keep the analysis as simple as possible, yet conclusive; consequently, sophistications have been generally omitted.

The only significant change in the present experimental setup is an additional safety requirement for containing any radioactive debris. Although relatively small amounts of contamination are involved, the experiments should be conducted either in a closed filter-vented vault, which could be built at General Atomic, or in the open at an expensive restricted access area. A vault facility seems particularly attractive, since it would permit a direct measurement of ablated tracer activity by debris sampling techniques.

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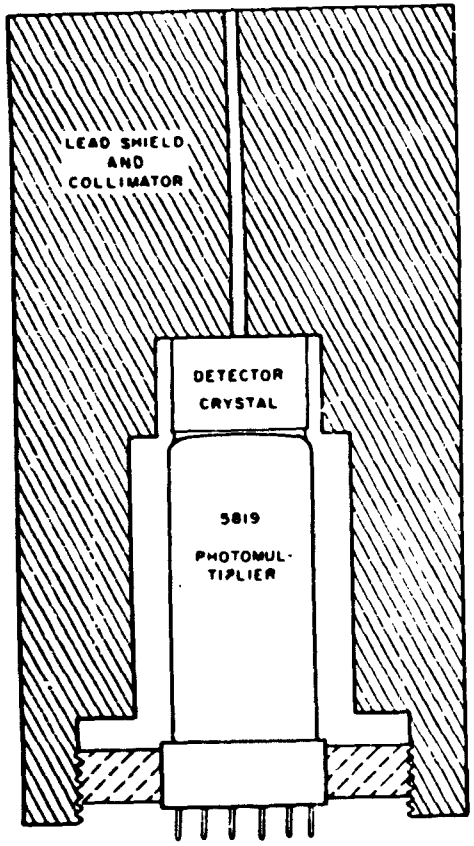

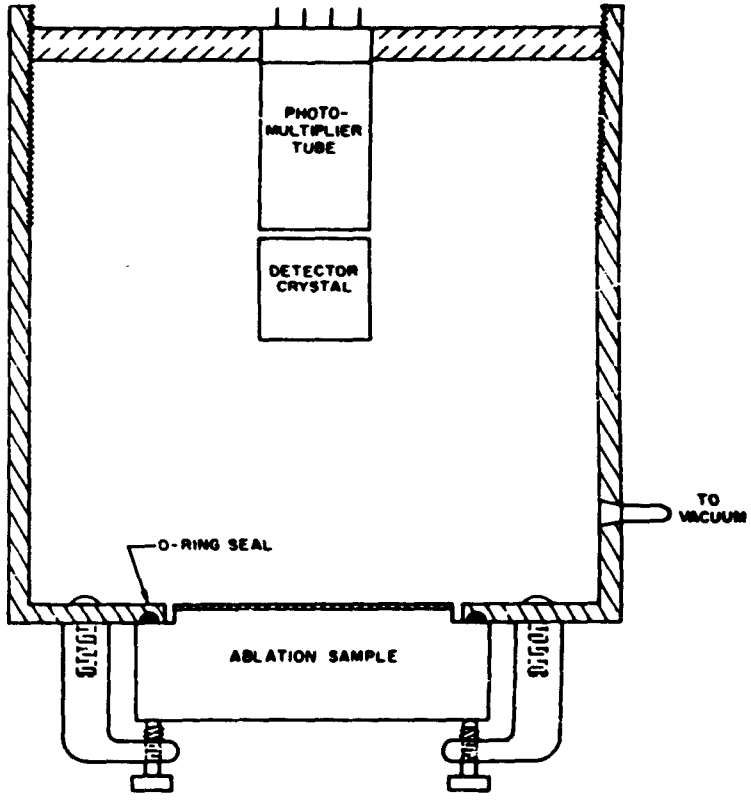

END

FIGURE

LARGE ANGLE COUNTER FOR MEASURING TOTAL ABLATION